J. Indian Soc. Coastal Agric. Res. 42(1):88-97(2024) https://doi.org/10.54894/JISCAR.42.1.2024.147322

Rice-Zero Tillage Potato-Green Gram and Conservation Agriculture Enable Sustainable Intensification in the Coastal Region

SUKANTA K. SARANGI[1#*], MOHAMMED MAINUDDIN[2], RICHARD W. BELL[3] and SAHEB DIGAR[1]

[1]ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town - 743 329, West Bengal, India

[2]CSIRO Environment, Canberra, ACT - 2601, Australia

[3]Centre for Sustainable Farming Systems, Food Futures Institute, Murdoch University, Murdoch, WA - 6150, Australia

Received: 10.01.2024 Accepted: 24.03.2024

Rice-fallow and rice-rice are important cropping systems in India next to rice-wheat. Rice-fallow system faces critical resource shortages such as irrigation water and encounters salinity whereas, rice-rice system is heavily dependent on extensive non-renewable natural resources with poor resource use efficiency and unsustainability. Sustainable cropping intensification options through on-station and on-farm research have been developed under a multi-institutional project funded by the Australian Centre for International Agricultural Research (ACIAR) during 2015-2022 to address these challenges. The results showed that rice followed by zero tillage planting of potato with paddy straw mulching (ZTPSM), and the rice-potato ZTPSM-green gram cropping patterns are the most promising systems compared to conventional rice-rice rotation. System rice equivalent yield increased from 11.7 t ha^{-1} in rice-rice to 20.2 t ha^{-1} in rice-potato ZTPSM - green gram (R-PZTPSM-GG). The soil salinity (EC$_e$) diminished to <3.6 dS m^{-1} due to ZTPSM from 5.29-6.36 dS m^{-1} under conventional practice. There is scope to sustainably intensify the rice-fallow lands to atleast 200% cropping intensity from the current 150% with additional net returns of ₹ 0.95 Lakhs ha^{-1}. In addition, the R-PZTPSM-GG system has a lower environmental footprint due to lower irrigation water (0.31 m^3 kg^{-1} rice-eq) requirement and lower carbon (10.1 t CO_2-eq ha^{-1}) emissions intensity than rice-rice system (1.19 m^3 kg^{-1} rice and 30.5 t CO_2-eq ha^{-1}).

(***Key words:*** *Boro rice, Carbon footprint, Economic, Greenhouse gas emission, Paddy straw mulching, Water footprint, Zero tillage*)

Cropping system sustainability for intensive resource use rotations such as rice-rice system of India occupying about 6 million hectares (M ha) of land has been a question in recent years due to poor resource use efficiency, micronutrient deficiency and deterioration of soil physical properties (Panda *et al.,* 2018). Similarly, in most of the rice-fallow land use system areas in the eastern states of India about 40-50% of the population is classed as multi-dimensionally (health, education and standard of living) poor (NITI Aayog, 2021). These regions are also disadvantaged by poverty, food insecurity, environmental vulnerability and limited livelihood opportunities. Their land resources are vulnerable to degradation due to combinations of natural, hydrological and anthropogenic factors. The major drivers for the degradation of land are salinization, acidification, waterlogging with fresh/brackish water, drainage congestion, erosion, etc. In the eastern states of India, about 10 M ha (Uttar Pradesh 0.35 M ha, Bihar and Jharkhand 2.20 M ha, West Bengal 1.72 M ha, Odisha 1.22 M ha, Madhya Pradesh and Chhattisgarh 4.3 M ha and Assam 0.54 M ha) of cultivable land remain fallow due to soil moisture depletion and irrigation water scarcity during the *Rabi* season after harvest of the *Kharif* rice (Kumar *et al.,* 2019).

Sustainable intensification of such land needs improved package of practices which conserves soil moisture, facilitates early crop establishment, ensures profitability and has a positive effect on soil health and environment (Sarangi *et al.,* 2021b). In these states, where irrigation facilities are available, *Boro* rice

**Corresponding author:* E-mail: sksarangicanning@gmail.com

#Present Address: ICAR-Central Institute for Women in Agriculture (CIWA), Bhubaneswar - 751 003, Odisha, India

is cultivated with intensive use of ground water for irrigation along with heavy inputs of fertilizers and plant protection chemicals. Our recent studies conducted in the salt-affected coastal zones of the Sundarbans, West Bengal revealed that profitable cropping system intensification is possible by the cultivation of arable crops such as potato under zero tillage (ZT) planting and paddy straw mulching (PSM) followed by cultivation of a pulse crop such as green gram with conservation of soil moisture, reduced use of irrigation water and less emission of greenhouse gases. In this paper, we present the results of our study on rice-rice and rice-ZTPSM potato-green gram cropping systems conducted in the Indian Sundarbans, West Bengal, India. We hypothesized that following zero tillage planting and paddy straw mulching in dry season crops, sustainable cropping system intensification is possible in the coastal region of India. Zero tillage will enable earlier plating, while paddy straw mulching will help in the conservation of soil moisture, reduction of irrigation water use and salinity.

MATERIALS AND METHODS

The study was conducted during 2016-2020 in the Sundarbans region of the Ganges Delta. The data for the rice-rice cropping system was collected from an on-station experiment conducted during 2016-17 and 2017-18 at the Indian Council of Agricultural Research (ICAR)-Central Soil Salinity Research Institute (CSSRI), Regional Research Station, Canning Town (Latitude: 22°15′ N, Longitude: 88°40′ E) and for rice-ZTPSM potato-green gram, data was collected from an on-farm experiment conducted at Gosaba island (Latitude: 22° 06.414′ N to 22°12.570′ N and Longitude: 88°46.326′ E to 88°52.152′ E) during 2018-19 and 2019-20. Both Canning Town and Gosaba are within the Sundarbans region with similar soil texture (>40% clay) and agro-climatic conditions (high annual rainfall of about 1800 mm mostly falling during the wet season, with a long dry season characterized by high soil and water salinity). The rice-rice and rice-ZTPSM potato-green gram cropping systems were evaluated in terms of rice equivalent yield (REY), economics (cost of cultivation, gross return, net return and benefit cost ratio), irrigation water use and greenhouse gas (GHG) emissions.

In both the cropping systems, during the wet (*Kharif*) season, tall and long duration rice was grown under rainfed conditions. The fertilizer dose of *Kharif* rice was 75-40-10 kg N-P_2O_5-K_2O ha^{-1}. In rice-rice cropping system, during the dry (*Boro*) season, rice was grown with the use of groundwater for irrigation. Groundwater was lifted from more than 500 m depth using pumps consuming electric energy. A fertilizer dose of 120-20-10 kg N-P_2O_5-K_2O ha^{-1} was applied to *Boro* rice crop as urea (46% N), single super phosphate (16% P_2O_5) and muriate of potash (60% K_2O), respectively. All of the P and K and 25% of the N were applied prior to land levelling. Half of the N was broadcast 21 days after transplanting (DAT) and the remaining 25% was broadcast at 60 DAT.

In rice-ZTPSM potato-green gram cropping system, after the harvest of rice, potato (cv. Kufri Pukhraj) was planted during the first week of December on wet soil with zero tillage. Tubers were sown at 10-15 cm hill to hill and 30-35 cm row to row distance. The potato experiment consisted of seven treatments *viz*., T_1: conventional ridge and furrow cultivation with soil application of nutrients, T_2: ZT planting+PSM @ 15 cm thickness (~9 t ha^{-1}) with broadcasting of fertilizers, T_3: ZT+PSM @ 15 cm thickness with foliar spray of water soluble fertilizers, T_4: ZT+PSM @ 20 cm thickness (~12 t ha^{-1}) with broadcasting of fertilizers, T_5: ZT+PSM @ 20 cm thickness with foliar spray of soluble fertilizers, T_6: ZT+PSM @ 25 cm thickness (~15 t ha^{-1}) with broadcasting of fertilizers and T_7: ZT+PSM @ 25 cm thickness with foliar spray of soluble fertilizers. The tubers were covered with dry compost/farm yard manure (FYM @ 5 t ha^{-1}), then NPK fertilizer (10-26-26) was applied, and finally the paddy straw was applied as per the treatment. Foliar spray (300 L ha^{-1} at 10 g L^{-1}) of water-soluble compound fertilizer (19-19-19 kg N-P_2O_5-K_2O) was given at 30 and 45 days after planting (DAP). The third foliar spray (300 L ha^{-1} at 2 g L^{-1}) was given at 60 DAP with 13-0-45 kg N-P_2O_5-K_2O for better tuber growth. Fertilizer dose for potato crop was 100-75-75 kg N-P_2O_5-K_2O ha^{-1}. Potato tubers were harvested from the end of February to the first week of March.

Immediately after the harvest of potato, green gram was sown and harvested within the second week of May. Rice Equivalent Yield (REY) was calculated by the formula (yield of rice × price of rice + yield of second crop, if any × price of second crop + yield of third crop, if any × price of third crop)/ price of rice). Soil salinity (0-15 cm soil depth) was measured as the electrical conductivity of saturation extract (EC_e) in dS m^{-1} using an electrical conductivity meter (Systronics India Ltd., Ahmedabad, Gujarat, India).

The economics of cropping systems were evaluated in terms of cost of cultivation, gross and net return. The cost of cultivation was worked out based on market prices of inputs. The input costs included costs of seed tubers, compost, chemical fertilizers, fungicides, irrigation and field operations. Labour for all the operations, including planting, application of paddy straw as mulch, compost for covering seed tubers, fertilizers, fungicides, irrigation water and harvesting was based on person days ha^{-1} assuming an 8 h working day. Gross returns were calculated by multiplying the crop yield (t ha^{-1}) with the respective market price (₹ t^{-1}). Net return is the gross return less cost of cultivation.The GHG emissions were estimated by use of the Cool Farm Tool software CFT v1.13 (https://coolfarmtool.org). Various input data as

Table 1. *Major input data used in the Cool Farm Tool software for estimation of greenhouse gas emissions*

Inputs	*Kharif* rice	*Boro* rice	Potato	Green gram
Grain/tuber yield (t ha^{-1})	6.14	5.51	18.14	1.50
Residue amount (t ha^{-1})	7.65	6.12	10.00	0.76
Soil type	Silty clay	Clay (fine)	Silty clay	Clay (fine)
Organic matter (%)	1.05	1.03	0.71	0.77
Soil organic carbon (%)	0.61	0.60	0.41	0.45
Soil pH	5.5-7.3	5.5-7.3	5.5-7.3	5.5-7.3
Flooding period (months)	5	4	-	-
Fertilizers (kg ha^{-1})				
Urea (46% N)	100	120	153.5	20
Super phosphate (21% P_2O_5)	40	20	-	20
Super phosphate (16% P_2O_5)	-	-	2.8	-
Potassium chloride (60% K_2O)	10	10	-	10
NPK (10-26-26)	-	-	283	-
NPK (19-19-19)	-	-	6	-
NPK (13-0-45)	-	-	0.6	-
Insecticide (kg ha^{-1})	2	2	-	
Fungicide (kg ha^{-1})	-	-	-	0.04
Field operational energy use				
Fuel use for tillage operations	Diesel	Diesel	-	-
Energy use for sowing/planting	Human	Diesel	Diesel	Diesel
Fuel use for harvesting	Diesel	Diesel	Diesel	Diesel
Irrigation	Rainfed	12 nos. (1384 mm) from borehole/well with pumping depth of 500 feet and horizontal distance of 50 m by electric source	4 nos. (355.3 mm) from on-farm storage pond by electric source	3 nos. (271.1 mm) from on-farm storage pond by electric source
Transport				
Mode (Road)	LGV diesel	LGV/CNG/LPG	LGV diesel	LGV/CNG/LPG
Weight (tonnes)	13.5	7	18	1.5
Distance (km)	0.25	0.2	5	0.2

per crops and cropping systems were entered into the software to get the emission value outputs (Table 1). Data were analyzed by using Statistical Tool for Agricultural Research (STAR) software developed by the International Rice Research Institute (IRRI) by using Eclipse Rice Client Platform and R language for crop scientists (http://bbi.irri.org). The treatment means were compared by least significant difference (LSD) values calculated by the use of standard error and the Student's t value using error degrees of freedom and 5% level of significance (Panse and Sukhatme, 1978).

RESULTS AND DISCUSSION

Performance of potato under conventional vs ZT planting with paddy straw mulching

Mean potato tuber yields significantly increased from 21.4 t ha^{-1} under conventional ridge planting to 32.0 t ha^{-1} under ZT planting with paddy straw mulching. The thickness of paddy straw mulch as well as nutrient management are also important factors for higher yield of potato under ZT planting. When 15 cm thick mulch (~9 t ha^{-1}) cover was used with broadcasting of fertilizers during 2018-19, the tuber yield was at par with conventional tillage. ZT planting with foliar application of nutrients had increased the yield of potato significantly. The irrigation water use was significantly reduced to 31.5 cm with ZTPSM compared to 47.7 cm under conventional cultivation practice. The reduction in irrigation water use in the ZTPSM was attributed to the effective use of carry over soil moisture from previous *Kharif* season due to early planting and reduction of evaporative loss by the straw mulch cover over the soil surface. The irrigation water productivity also increased to 1026 kg tuber ha^{-1} cm^{-1} in the developed package of potato cultivation from 448 kg tuber ha^{-1} cm^{-1} under conventional practice (Table 2). There was a significant reduction in soil salinity development in the topsoil (0-15 cm), which is the main root zone for the *Rabi* season crops. The soil salinity was 5.29 - 6.36 dS m^{-1} in conventional tillage practice of making ridges and furrows. Due to the ZT planting with PSM, the soil salinity was reduced, to the range of 2.19-3.58 dS m^{-1}. In the coastal region of India, potato crop after *Kharif* rice is grown under irrigated situation by utilizing the conserved rainwater in water harvesting structures such as dug out pond. However, this crop cultivation is very limited in the salt-affected region due to the adverse impact of salinity on crop growth and yield (Sanwal *et al.,* 2022). In the present study, tuber yield was significantly higher due to ZT planting with PSM, which enabled earlier crop establishment and mulching reduced salinity. To get better results of higher yield, reduced salinity and irrigation water productivity, PSM with more than 15 cm thickness (> 9 t ha^{-1}) is essential. When potato crop is grown under conventional systems, there is a delay in crop establishment, as a result, the crop faces higher temperature and salinity regimes and ultimately lower production. Performance of potato crop is significantly affected by heat and drought stress during tuber bulking (Vanongeval and Gobin, 2023).

There was a significant reduction in the soil salinity level due to ZT planting combined with PSM compared to the conventional ridge and furrow cultivation of potato. The soil salinity was well below the critical level of 4 dS m^{-1} generally considered the threshold for saline soils (Shrivastava and Kumar, 2015). However, in another study (Paul *et al.,* 2020), when no crop residues are used as mulch in wet clay soils, heavy soil disturbance, such as with bed planting has the potential to decrease soil salinity by maintaining a higher solute potential in the upper soil layers. Another option of coastal salinity management is the leaching and flushing of salts through irrigation water followed by drainage to remove salts from the crop root zone (Mainuddin *et al.,* 2019).

Yield, profitability and water footprint of crops and cropping systems

The new cropping system (rice-ZTPSM potato-green gram) produced a rice equivalent yield (REY) of 20.2 t ha^{-1} which was almost double than that recorded under the rice-rice cropping system (11.7 t ha^{-1}). Among the individual crops, highest cost of cultivation was incurred for potato cultivation, due to higher seed rate requirement as well as the price of seed tubers. *Boro* rice cultivation is also cost intensive due to the investment in irrigation infrastructure as well as the cost of irrigation. Though the new cropping system involved a higher cost of cultivation, it was profitable with other advantages. The gross and net returns from the new cropping system were higher compared to rice-rice system. This cropping system was also highly profitable as the net return was

Table 2. *Effect of paddy straw mulching and foliar spray of nutrients on the performance of zero tillage sown potato in coastal salt-affected soils*

Treatments	Tuber yield (t ha^{-1})		Irrigation water use (cm)		Water productivity (kg tuber ha^{-1} cm^{-1})		Soil salinity (EC_e, dS m^{-1})	
	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20
T_1	21.5	21.2	49.5	46.0	434	463	6.36	5.29
T_2	22.4	25.0	35.9	33.2	628	748	3.58	2.62
T_3	29.6	28.3	35.9	32.9	830	853	3.45	2.56
T_4	32.3	27.9	32.0	29.1	1005	958	3.12	2.43
T_5	37.9	32.7	31.9	28.9	1185	1130	2.56	2.41
T_6	40.1	30.9	30.8	28.1	1299	1099	2.45	2.23
T_7	41.5	34.8	30.9	28.1	1340	1239	2.33	2.19
LSD (P=0.05)	4.17	3.10	2.0	2.03	138.2	106.2	0.31	0.27

T_1: Ridge and furrow cultivation with soil application of nutrients, T_2: Zero tillage planting with paddy straw mulching (ZT+PSM) @ 15 cm thickness with broadcasting of fertilizers, T_3: ZT+PSM @ 15 cm thickness with foliar spray of water soluble fertilizers, T_4: ZT+PSM @ 20 cm thickness with broadcasting of fertilizers, T_5: ZT+PSM @ 20 cm thickness with foliar spray of soluble fertilizers, T_6: ZT+PSM @ 25 cm thickness with broadcasting of fertilizers and T_7: ZT+PSM @ 25 cm thickness with foliar spray of soluble fertilizers

₹ 2.06 lakh ha^{-1} year^{-1}, compared to ₹ 1.12 lakh ha^{-1} year^{-1} in the rice-rice cropping system. The higher yield and profitability under the new cropping system are obtained with less irrigation water footprint (0.31 m^3 kg^{-1} rice equivalent yield) compared to 1.19 m^3 kg^{-1} rice equivalent yield in the rice-rice system (Table 3).

The innovative crop establishment in the wet soil by ZT planting utilized the carry over soil moisture, subsequently PSM reduced evaporation loss and conserved soil moisture, thereby this method required less irrigation water input for successful potato cultivation. Good quality irrigation water is a precious and scarce resource in the salt affected coastal region of the Ganges Delta (Mainuddin *et al.,* 2020). Reducing the water footprint in agriculture is a key factor for human welfare and sustainability on the planet (Bhatt *et al.,* 2021). In the rice-rice cropping system, the second crop of rice (*Boro*), requires heavy irrigation water inputs to the tune of 1444 mm, however, this depends on the sowing date and duration of the rice variety grown in the coastal region (Sarangi *et al.,* 2021a). The double rice system also had significantly higher water footprint compared to rice-ratoon rice and rice-wheat system in China (Zhou *et al.,* 2022). This suggests reduced water footprint could be a widespread benefit from replacing the double rice system with alternatives.

Table 3. *Rice equivalent yield (REY), profitability and water footprint of rice-rice and rice-ZTPSM potato-green gram cropping systems in the Ganges Delta*

Crops/cropping systems	REY (t ha^{-1})	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	Irrigation water use (m^3 ha^{-1})	Water footprint (m^3 kg^{-1} REY)
Kharif rice	6.14	39,000	1,04,380	65,380	-	-
Boro rice	5.51	47,000	93,670	46,670	13840	2.51
Potato*	9.60	75,200	1,63,200	88,000	3553	0.37
Green gram*	4.42	22,000	75,140	53,140	2711	0.61
Rice-rice	11.65	86,000	1,98,050	1,12,050	13840	1.19
Rice-potato*-green gram*	20.16	1,36,200	3,42,720	2,06,520	6264	0.31
LSD (P=0.05)	0.79	-	-	-	-	-

*Zero tillage planting with paddy straw mulching (ZTPSM)

Environmental footprints / greenhouse gases (GHGs) emission from crops and cropping systems

GHGs emission from Kharif rice cultivation

Rice is the major crop during the *Kharif* season in the coastal region due to the high rainfall and low-lying topography. About 4.59 t of CO_2-eq ha^{-1} (Fig. 1a) was estimated for GHGs emission, of which 77% was due to paddy methane emission and rest to the fertilizer production and use, field energy use for land preparation and other tillage operations while a very small fraction was attributed to crop protection and transportation operations.

GHGs emission from Boro rice cultivation

Total estimated GHGs emission from *Boro* rice cultivation was 25.92 t of CO_2-eq ha^{-1} (Fig. 1a), where the major cause of emission was due to use of energy (electricity) for pumping of ground water for irrigation at a depth of 500 ft below the field level. Standing water

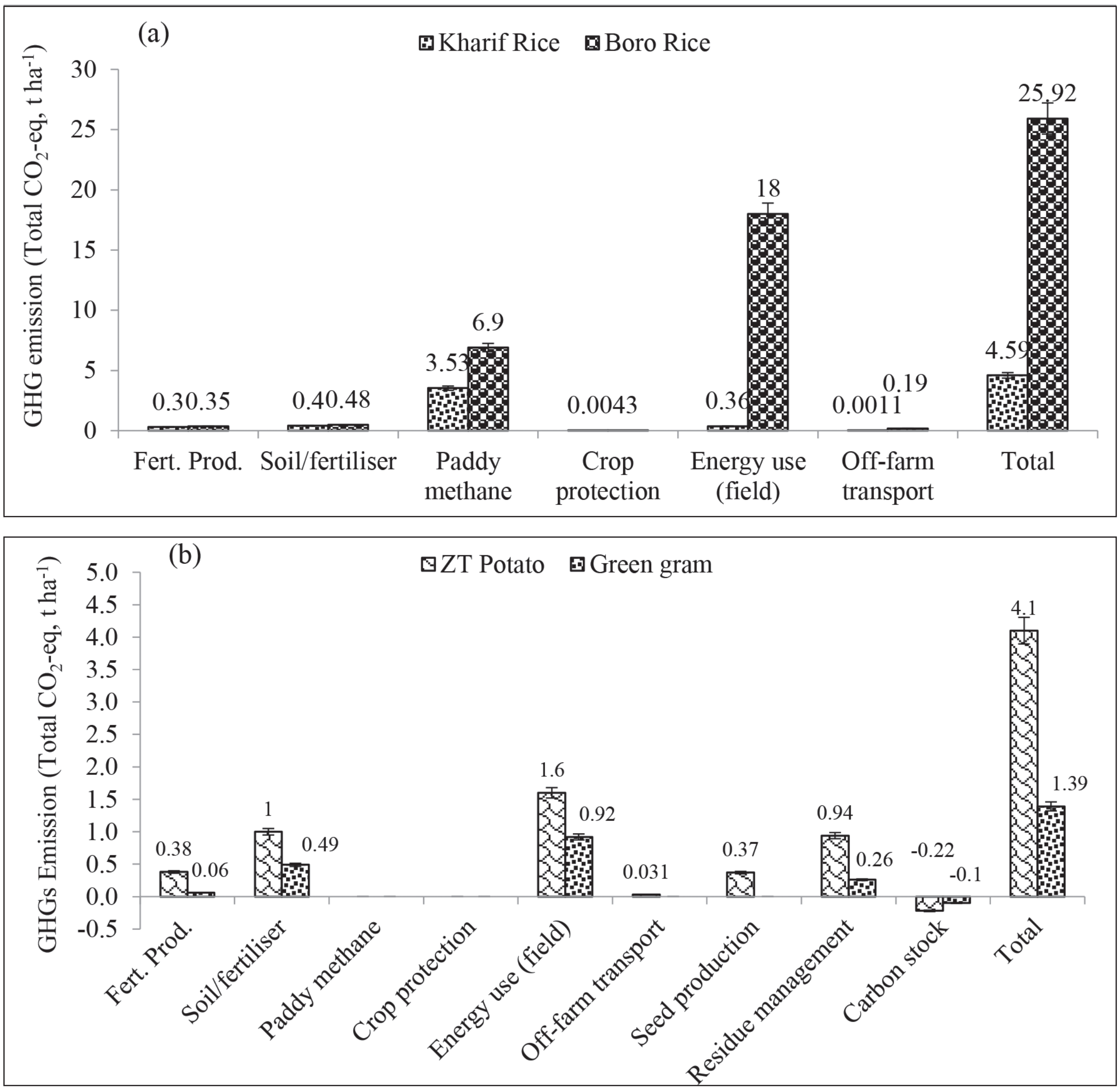

Fig. 1. *Environmental foot prints of (a)Kharif and Boro rice, (b) potato crop under zero tillage planting and paddy straw mulching and green gram cultivation in the coastal region of Sundarbans. The GHG emissions were estimated by use of Cool Farm Tool software CFT v 1.13 (https://coolfarmtool.org/)*

conditions cause anaerobic conditions and methane emissions, which was the second most important factor (6.90 t of CO_2-eq ha^{-1}) for GHGs emission from *Boro* rice cultivation. Other important factors were fertilizer production and use, use of crop protection chemicals and energy use for transportation of the produce.

GHGs emission from improved potato cultivation

Potato cultivation by following the best practices for coastal saline soils, resulted in emissions of 4.10 t of CO_2-eq ha^{-1} (Fig.1b). Potato is an irrigated crop which needs energy for irrigation water application, energy for planting, application of inputs and harvesting. The field energy use is the major component followed by fertilizer application and residue management. However, recycling of crop residues in the improved package of practices contributes to carbon stock (0.22 t of CO_2 - eq ha^{-1}). Diversification of *Boro* rice area to potato cultivation with improved practices, significantly reduced the GHGs emission from 25.92 to 4.10 t of CO_2-eq ha^{-1}.

GHGs emission from improved green gram cultivation

There is an opportunity for cultivation of green gram after harvest of potato, if the zero tillage planting practices are followed. Being a legume crop, it also fixes atmospheric nitrogen in the root zone. The total GHGs emissions due to green gram cultivation was estimated to be 1.39 t of CO_2-eq ha^{-1} (Fig.1b). This crop also contributed to the soil carbon stock to the extent of 0.1 t of CO_2-eq ha^{-1}. The total GHGs emissions from potato and green gram were estimated to be 5.49 t of CO_2-eq ha^{-1}, which is significantly lesser than the emission from *Boro* rice (25.92 t of CO_2-eq ha^{-1}).

GHGs emission from cropping systems

The system GHG emissions were computed for rice-rice (Fig. 2a) and rice-potato-green gram rotations (Fig. 2b). Continuation of the rice-rice system is a threat to environmental pollution by the emission of higher amounts of GHGs, mostly due to high levels of field energy use and paddy methane emissions. The alternative cropping system following zero tillage planting of potato after harvest of *Kharif* rice and growing a pulse crop (green gram) contributes to sustainable intensification by reducing the GHGs emission to about one third of the emissions from rice-rice system. The lower GHGs emission from the rice-potato-green gram cropping system is due to lower use of irrigation water, recycling of crop residues for soil organic carbon sequestration and inclusion of legume crops in rotation.

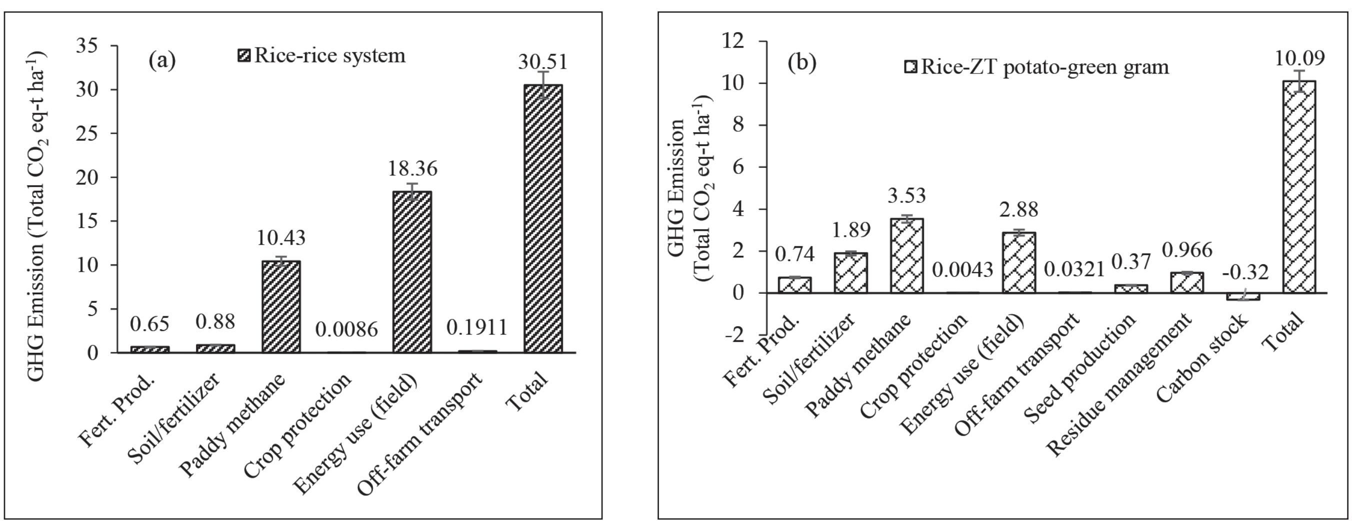

Fig. 2. *Environmental foot print of (a) rice-rice and (b) rice-ZT potato-green gram cropping system in coastal salt affected region of Sundarbans, India. GHG emissions were estimated by use of Cool Farm Tool software CFT v1.13 (https://coolfarmtool.org/)*

Agriculture is a source as well as sink for greenhouse gases (GHGs) emission, there are now more and more voices about the need to reduce emissions (Golasa *et al.,* 2021). Reports suggest that converting from continuous flooding to intermittent flooding lowers CH_4 emissions by approximately 18% (Cowan *et al.,* 2021); however, in the coastal region during the *Kharif* season, there is no scope for drainage of excess water as all the surrounding fields are full with standing water. Though we have observed higher GHGs emission per unit area from *Boro* rice cultivation compared to *Kharif* rice, the aggregate emissions during the *Kharif* season are significantly higher due to the higher acreage under the *Kharif* rice across monsoon Asia (Ouyang *et al.,* 2023). The alternative cropping system involving ZT potato with PSM followed by green gram crop has been found to be environment friendly due to lower GHGs emission. Inclusion of green gram as a pulse crop has several advantages to soil, human beings and animals. Pulse crops are important components in sustainable human and animal diets as well as for cropping systems (Tidaker *et al.,* 2021). Synthetic N fertilizers account for 10.6% of agricultural emissions and 2.1% of global GHG emissions (Menegat *et al.,* 2022). Legume crops, fix atmospheric nitrogen, thereby reducing the need for added fertilizers (Gustafson, 2017), hence lower GHG emissions.

CONCLUSION

Rice-potato-green gram cropping system by following conservation agriculture practices such as zero tillage planting of potato and green gram and recycling of paddy straw as a mulch both in potato and green gram enabled sustainable intensification of rice-fallow lands in the coastal saline zones. By following zero tillage planting with paddy straw mulching, potato tuber yield increased to the extent of 35.50 t ha^{-1} from 21.35 t ha^{-1} under conventional ridge and furrow cultivation. About 18 cm of irrigation water can be saved by zero tillage planting and paddy straw mulching in potato. System rice equivalent yield increased from 11.65 t ha^{-1} in rice-rice cropping system to 20.16 t ha^{-1} in rice-potato ZTPSM-green gram cropping system. Under the alternative cropping system, the soil salinity (EC_e) diminished to 2.19-3.58 dS m^{-1} from 5.29-6.36 dS m^{-1} under conventional practice. There is scope to sustainably intensify the rice-fallow lands to 200% from the current 145% and to almost double net returns (₹ 2.06 Lakhs ha^{-1}) from the existing ₹1.12 Lakhs ha^{-1}. Not only does it increase net return but the rice-potato-green gram system has lower irrigation water (0.31 m^3 kg^{-1} rice-eq) and carbon (10.09 t CO_2-eq ha^{-1}) footprints than rice-rice system (1.19 m^3 kg^{-1} rice and 30.51 t CO_2-eq ha^{-1}). Total irrigation water use was significantly reduced to 6264 m^3 ha^{-1} in rice-potato ZTPSM-green gram from 13840 m^3 ha^{-1} under rice-rice system.

ACKNOWLEDGEMENT

This research was funded by the Australian Centre for International Agricultural Research (ACIAR) under the project “Mitigating risk and scaling-out profitable cropping system intensification practices in the salt-affected coastal zones of the Ganges Delta” (LWR/2014/073 V5 Phase 2). The GHG emissions were estimated by use of the Cool Farm Tool software CFT v1.13.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

REFERENCES

Bhatt, R., Hossain, A., Busari, M.A. and Meena, R.S. (2021). Water footprint in rice-based cropping systems of South Asia. In: *Agroecological Footprints Management for Sustainable Food System,* A. Banerjee, R.S. Meena, M.K. Jhariya and D.K. Yadav (eds,). Springer, Singapore. https://doi.org/10.1007/978-981-15-9496-0_9.

Cowan, N., Bhatia, A., Drewer, J., Jain, N., Singh, R., Tomer, R., Kumar, V., Kumar, O., Prasanna, R., Ramakrishnan, B., Kumar, D., Bandyopadhyay, S.K., Sutton, M. and Pathak, H. (2021). Experimental comparison of continuous and intermittent flooding of rice in relation to methane, nitrous oxide and ammonia emissions and the implications for nitrogen use efficiency and yield. *Agriculture, Ecosystems and Environment* **319**: 107571. https://doi.org/10.1016/j.agee.2021.107571.

Golasa, P., Wysokinski, M., Golasa, W.B., Gradziuk, P., Golonko, M., Gradziuk, B., Siedlecka, A. and

Gromada, A. (2021). Sources of greenhouse gas emissions in agriculture, with particular emphasis on emissions from energy used. *Energies* **14**(13): 3784. https://doi.org/10.3390/en14133784.

Gustafson, D.I. (2017). Greenhouse gas emissions and irrigation water use in the production of pulse crops in the United States. *Cogent Food and Agriculture* **3**: 1334750. https://doi.org/10.1080/23311932.2017.1334750.

http://bbi.irri.org/products. *STAR-Statistical Tool for Agricultural Research.* Download Release Version: R-Packages 1.5 STAR 2.0.1. Accessed on 07 August 2023.

https://coolfarmtool.org/. *Cool Farm Tool (CFT v 1.13). An Online Greenhouse Gas, Water And Biodiversity Calculator.* Accessed on 07 August 2023.

Kumar, R., Mishra, J.S., Upadhyay, P.K. and Hans, H. (2019). Rice fallows in the eastern India: Problems and prospects. *Indian Journal of Agricultural Sciences* **89**(4): 567-577.

Mainuddin, M., Maniruzzaman, M., Gaydon, D.S., Sarkar, S., Rahman, M.A., Sarangi, S.K., Sarker, K.K. and Kirby, J.M. (2020). A water and salt balance model for the polders and islands in the Ganges Delta. *Journal of Hydrology* **587**: 125008. https://doi.org/10.1016/j.hydrol.2020.125008.

Mainuddin, M., Rahman, M.A., Maniruzzaman, M., Sarker, K.K., Mandal, U.K., Nanda, M.K., Gaydon, D.S., Sarangi, S.K., Sarkar, S., Yu, Y., Islam, M.T. and Kirby, M. (2019). The water and salt balance of polders/islands in the Ganges delta. *Journal of the Indian Society of Coastal Agricultural Research* **37**(2): 45-50.

Menegat, S., Ledo, A. and Tirado, R. (2022). Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. *Scientific Reports* **12**: 14490. https://doi.org/10.1038/s41598-022-18773.

NITI Aayog. (2021). *India - National Multidimensional Poverty Index Baseline Report 2021*. NITI Aayog, Government of India, New Delhi, India. https://www.niti.gov.in/sites/default/files/2021-11/National_MPI_India-11242021.pdf.

Ouyang, Z., Jackson, R.B., McNicol, G., Fluet-Chouinard, E., Runkle, B.R.K., Papale, D., Knox, S.H., Cooley, S., Delwiche, K.B., Feron, S., Irvin, J.A., Malhotra, A., Muddasir, M., Sabbatini, S., Alberto, M.C.R., Cescatti, A., Chen, C.L., Dong, J., Fong, B.N., Guo, H., Hao, L., Iwata, H., Jia, Q., Ju, W., Kang, M., Li, H., Kim, J., Reba, M.L., Nayak, A.K., Roberti, D.R., Ryu, Y., Swain, C.K., Tsuang, B., Xiao, X., Yuan, W., Zhang, G. and Zhang, Y. (2023). Paddy rice methane emissions across Monsoon Asia. *Remote Sensing of Environment* **284**: 113335. https://doi.org/10.1016/j.rse.2022.113335.

Panda, B.B., Satapathy, B.S., Nayak, A.K., Tripathi, R., Shahid, M., Mohanty, S., Bhaduri, D., Khanam, R. and Nayak, P.K. (2018). Agro ecological intensification of rice-based cropping system. In: *Rice Research for Enhancing Productivity, Profitability and Climate Resilience.* H. Pathak, A.K. Nayak, M. Jena, O.N. Singh, P. Samal and S.G. Sharma (eds.), ICAR-National Rice Research Institute, Cuttack, Odisha, India. pp. 258-274. Available online at: https://icar-nrri.in/wp-content/uploads/2019/02/Rice_Research_book_nrri.pdf.

Panse, V.G. and Sukhatme, P.V. (1978). *Statistical Methods for Agricultural Workers,* Indian Council of Agricultural Research, New Delhi, India. 361 p.

Paul, P.L.C., Bell, R.W., Barrett-Lennard, E.G. and Kabir, E. (2020). Variation in the yield of sunflower (*Helianthus annuus* L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil and Tillage Research* **197**: 104489. https://doi.org/10.1016/j.still.2019.104489.

Sanwal, S.K., Kumar, P., Kesh, H., Gupta, V.K., Kumar, A., Kumar, A., Meena, B.L., Colla, G., Cardarelli, M. and Kumar, P. (2022). Salinity stress tolerance in potao cultivars: Evidence from physiological and biochemical traits. *Plants (Basel)* **11**(14): 1842. https://doi.org/10.3390/plants11141842.

Sarangi, S.K., Mainuddin, M., Maji, B., Mahanta, K.K., Digar, S., Burman, D., Mandal, U.K., Mandal, S. (2021a). Optimum sowing date and salt tolerant variety boost rice (*Oryza sativa* L.) yield and water productivity during *Boro* season in the Ganges Delta. *Agronomy* **11**(12): 2413. https://doi.org/10.3390/agronomy11122413.

Sarangi, S.K., Maji, B., Sharma, P.C., Digar, S., Mahanta, K.K., Burman, D., Mandal, U.K., Mandal, S. and Mainuddin, M. (2021b). Potato (*Solanum tuberosum* L.) cultivation by zero tillage and paddy straw mulching in the saline soils of the Ganges Delta. *Potato Research* **64**(2): 277-305. https://link.springer.com/article/10.1007%2Fs11540-020-09478-6.

Shrivastava, P. and Kumar, R. (2015). Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences* **22**(2): 123-131. https://doi.org/10.1016/j.sjbs.2014.12.001.

Tidaker, P., Potter, H.K., Carlsson, G. and Röös, E. (2021). Towards sustainable consumption of legumes: How origin, processing and transport affect the environmental impact of pulses. *Sustainable Production and Consumption* **27**: 496-508. https://doi.org/10.1016/j.spc.2021.01.017.

Vanongeval, F. and Gobin, A. (2023). Adverse weather impacts on winter wheat, maize and potato yield gaps in northern Belgium. *Agronomy* **13**(4): 1104. https://doi.org/10.3390/agronomy13041104.

Zhou, Y., Liu, K., Harrison, M.T., Fahad, S., Gong, S., Zhu, B. and Liu, Z. (2022). Shifting rice cropping systems mitigates ecological footprints and enhances grain yield in central China. *Frontiers in Plant Science* **13**: 895402. https://doi.org/10.3389/fpls.2022.895402.